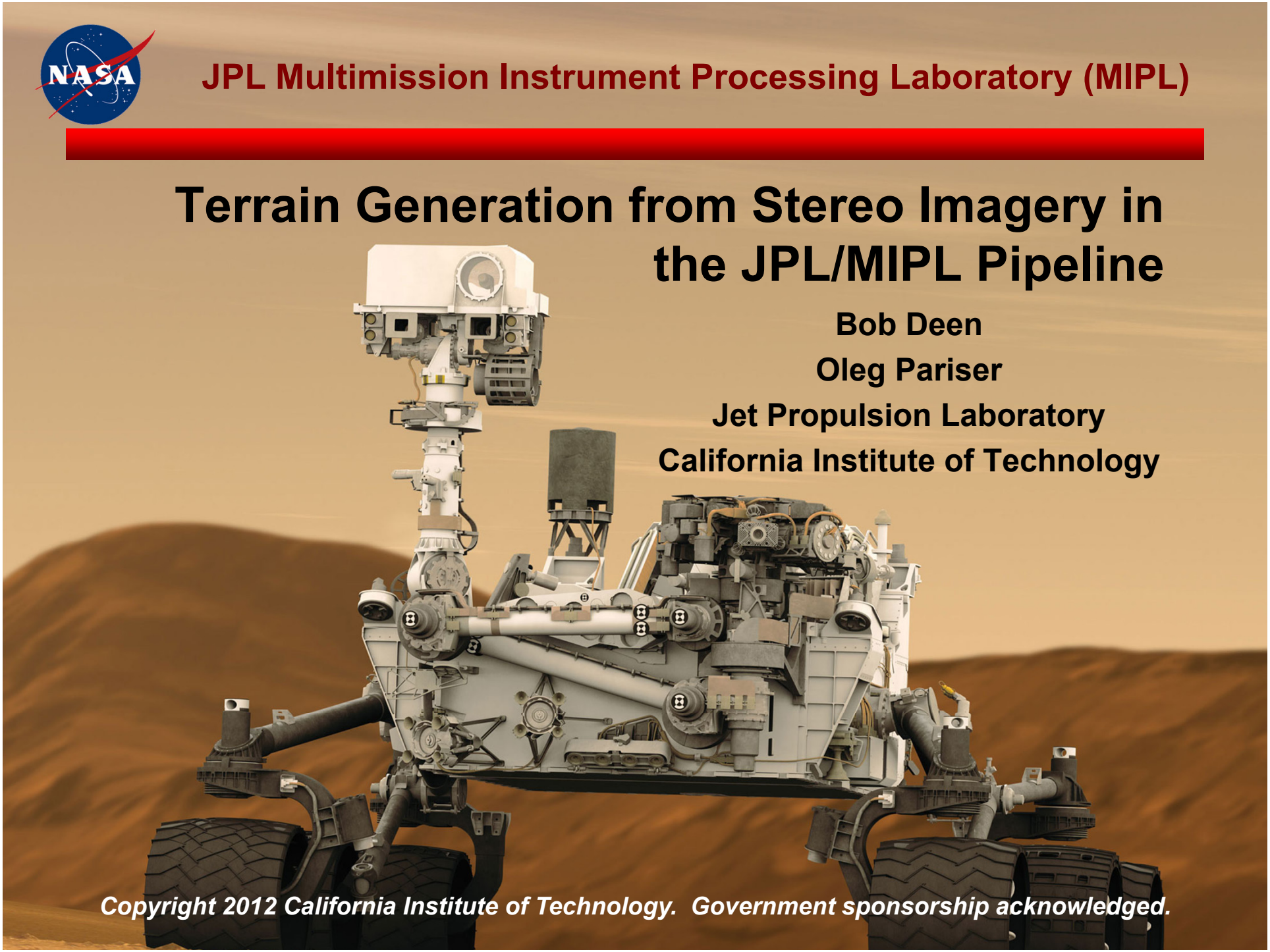

JPL Multimission Instrument Processing Laboratory (MIPL)

Terrain Generation from Stereo Imagery in the JPL/MIPL Pipeline

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Introduction

- **Multimission Image Processing Lab (MIPL) at JPL is responsible for (among other things) the ground-based operational image processing of all the recent in-situ Mars missions**
  - Mars Pathfinder
  - Mars Polar Lander
  - Mars Exploration Rovers (MER)
  - Phoenix
  - Mars Science Lab (MSL)
- **Most software is multimission, shared across all these missions**
- **Terrains and meshes are probably the most important products from MIPL for in-situ operations**
  - XYZ data is source of Maestro/MSLICE range information
    - Science Planner tool
  - Rover Planners plan drives using meshes
  - Arm operators use reachability maps derived from XYZ and surface normals
  - Scientists use terrain data to analyze geomorphology, photometry, etc.

Linearization

- **Linearization converts camera model to linear form**
  - Removes fish-eye from hazcams, radial optical distortion
  - Straight lines in the world are straight on linearized images
  - Epipolar-aligns stereo images
    - In practice, results can be up to 5 lines off (Spirit front hazcams)
- **Linearization Pros**
  - Much simpler and faster to compute
  - Models are easier to use
  - 1-D correlators can be used, at least at reduced resolution
- **Linearization Cons**
  - Introduces interpolation noise into images
    - Therefore slightly less accurate
  - Results are not coregistered with EDR's
  - Linearization done w.r.t. a specific image; must be re-done for another stereo partner
    - e.g. standard vs. long-baseline stereo
- **For MER, all terrain work is done with linearized images**
  - Non-linearized terrains occasionally made as special products (for science requests)
- **For MSL, baseline is to do both**
  - Non-linearized terrains at low compute priority

Raw and Linearized Image

Opportunity front hazcam, sol 2819. Raw on left, linearized on right

Terrain-Related Products

- **Disparity maps**
- **XYZ point clouds**
  - Primary product
- **Range maps**
- **Surface normals**
- **Range error maps**
  - New, still under development
- **Slopes and slope-related maps**
- **Arm reachability maps**
- **Meshes**

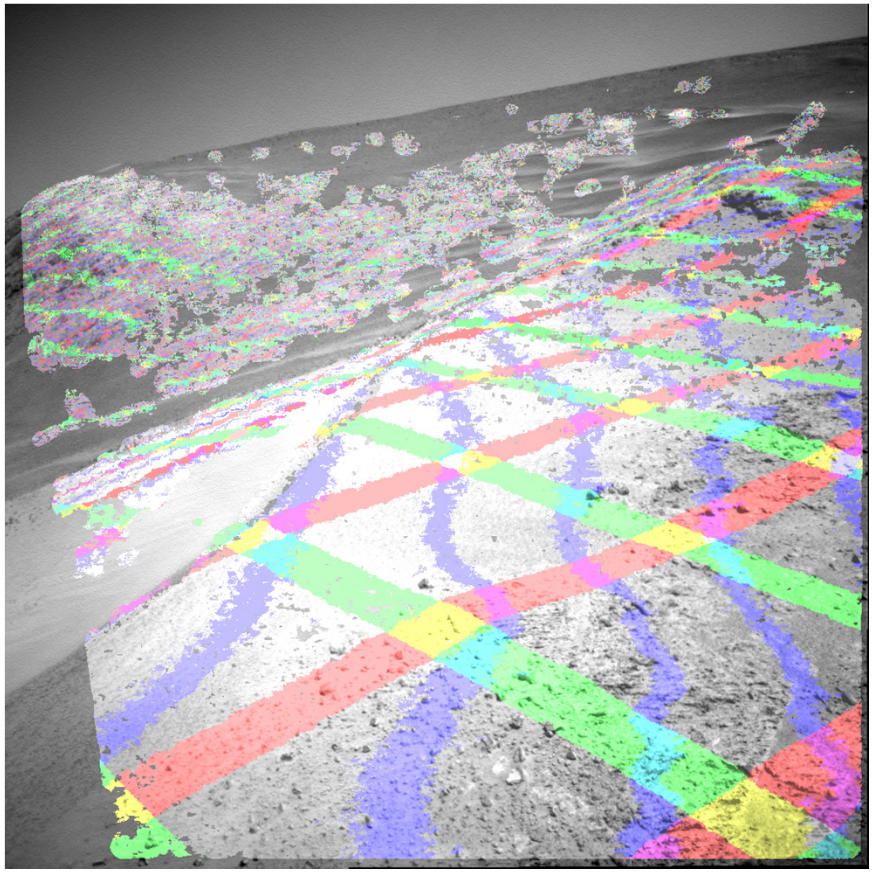
Algorithm Overview - Disparity

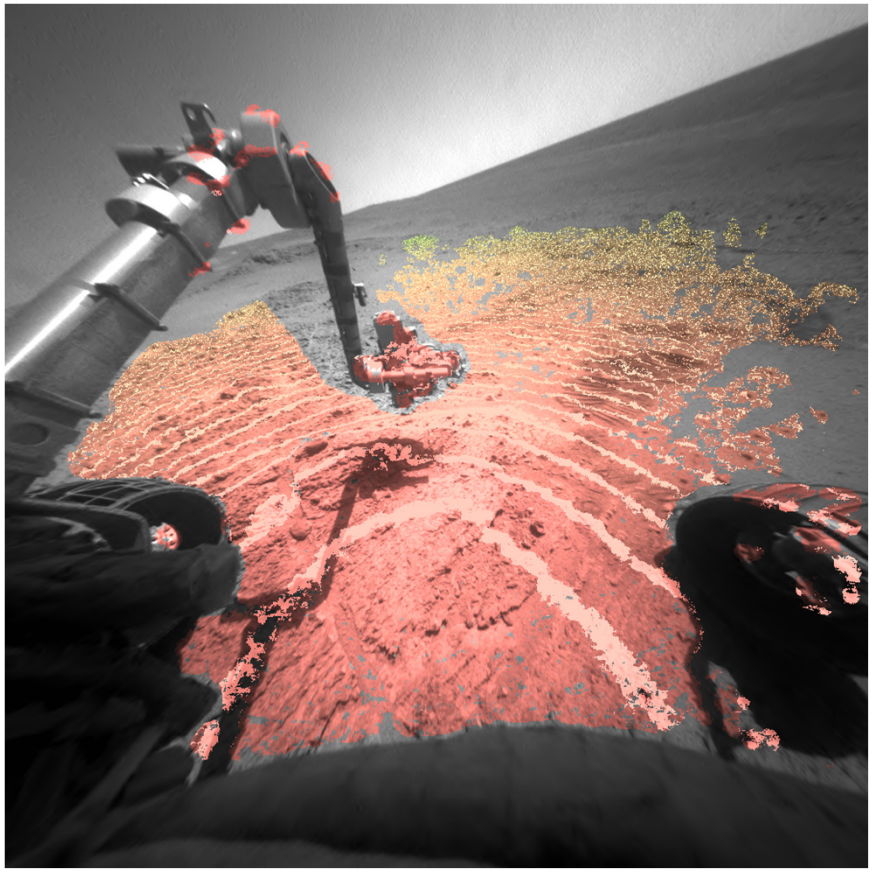
- **2-D correlation**
  - Compensates for epipolar alignment errors
- **Standard cross-correlation metric**
- **Uses modification of Gruen algorithm**
  - Affine transform + xy terms to map template
  - Amoeba simplex minimization algorithm to determine parameters
- **Consistency check of L->R and R->L correlations**
  - New for MSL, being back-ported to MER
- **Requires starting point for each pixel**
  - Can be reduced resolution; pyramids up to full res
  - 1-D flight correlator at reduced resolution used most commonly
  - Can also use assumed surface, or reversed or unlinearized disparity
- **More sophisticated algorithms possible (SIFT etc) but this works well**
  - Much computer vision research assumes a man-made world
    - Assumptions such as linear walls or sharp corners do not apply
- **Stereo only**
  - Multi-view systems get incredible results but we're data rate limited
    - Only on rare occasions do we get enough data to consider this
- **Require calibrated cameras**
  - Unconstrained techniques similarly require too much data

Algorithm Overview – XYZ Generation

- **XYZ's generated by simple geometric triangulation from disparity**
  - Project rays using camera models, find intersection (closest approach)
  - Chooses a point midway between the view rays at closest approach
    - Thus, point not exactly on either view ray
- **Results refined using a series of filters to remove bad points**
  - Missing correlation
  - Excessive raw or average line disparity
  - Not computable, diverging rays
  - Exceeding Z limits
  - Excessive miss distance or miss distance per range
  - Exceeding range limit (based on baseline)
  - Exceeding spike value (too far from neighbors in XYZ space)
  - Remove outliers (isolated points with not enough valid neighbors)

XYZ and Range Image



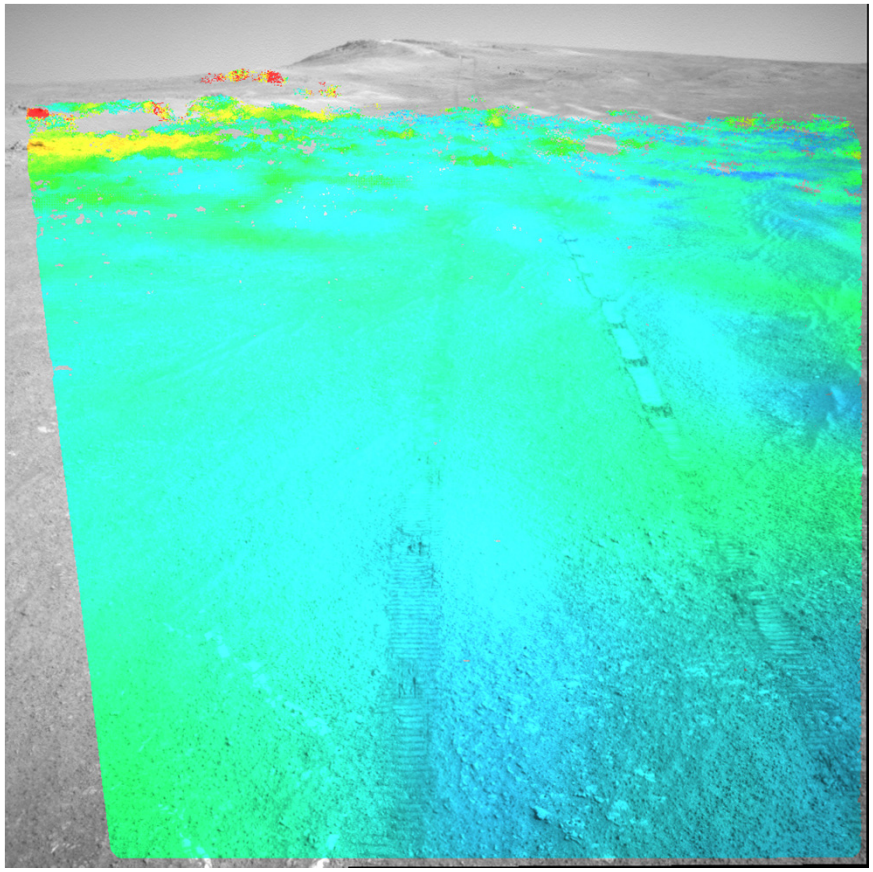


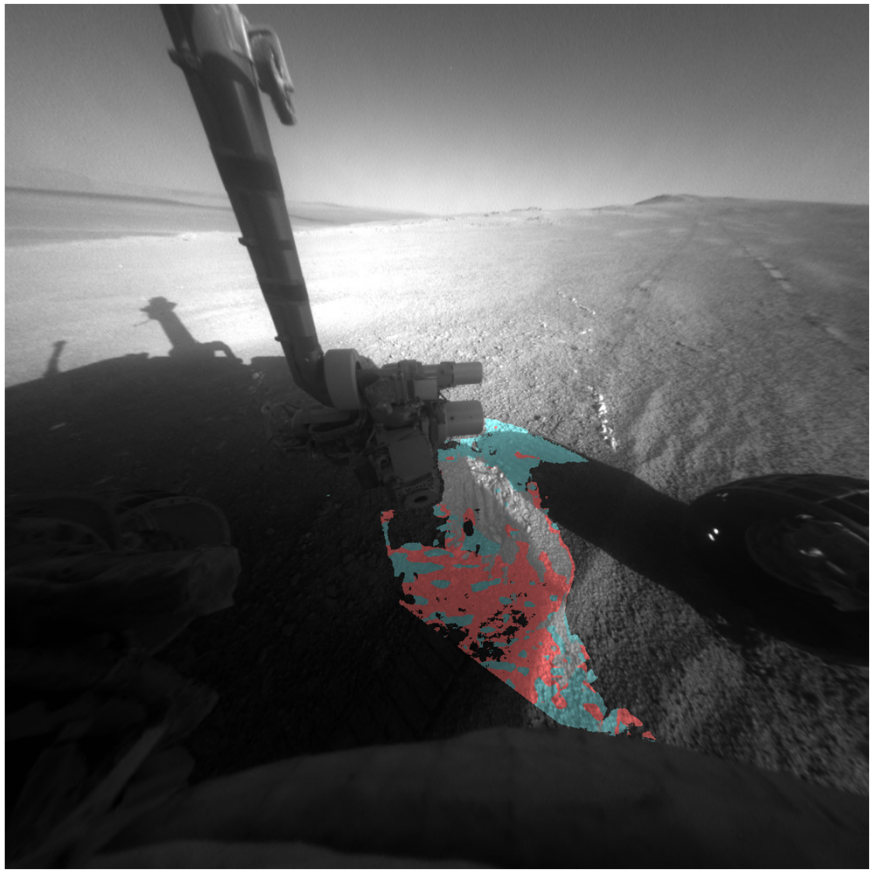
Left: Opportunity navcam, sol 2820; XYZ shows lines of constant X (red) and Y (green) at 1m spacing, with constant Z (blue) at 0.1m.
Right: Front hazcam, sol 2819; range has 1m spacing

Algorithm Overview - others

- **Range Maps**
  - Simple Cartesian distance from camera to XYZ point
- **Surface Normals**
  - Fits plane to neighboring pixels, with consistency checks
  - Computed on arm (instrument)-sized and rover-sized patches
- **Slope and Slope-Related Maps**
  - Computed from rover-sized surface normal
  - Slope, slope heading, northerly tilt, solar energy, etc.
- **Arm Reachability Maps**
  - Determines which pixels can be reached by each arm instrument
  - Uses FSW arm kinematics and collision models
    - Same algorithms as flight software uses for safety checks
  - Based on XYZ and surface normal
  - Also preload maps, surface roughness
  - Contributed by arm FSW team

Slope and Reachability Image





Left: Slope from navcam, sol 2965. Colors indicate slope; 0-10 degrees is blue->red.
Right: Arm reachability from front hazcam, sol 2965. Colors indicate different instruments or arm configurations.

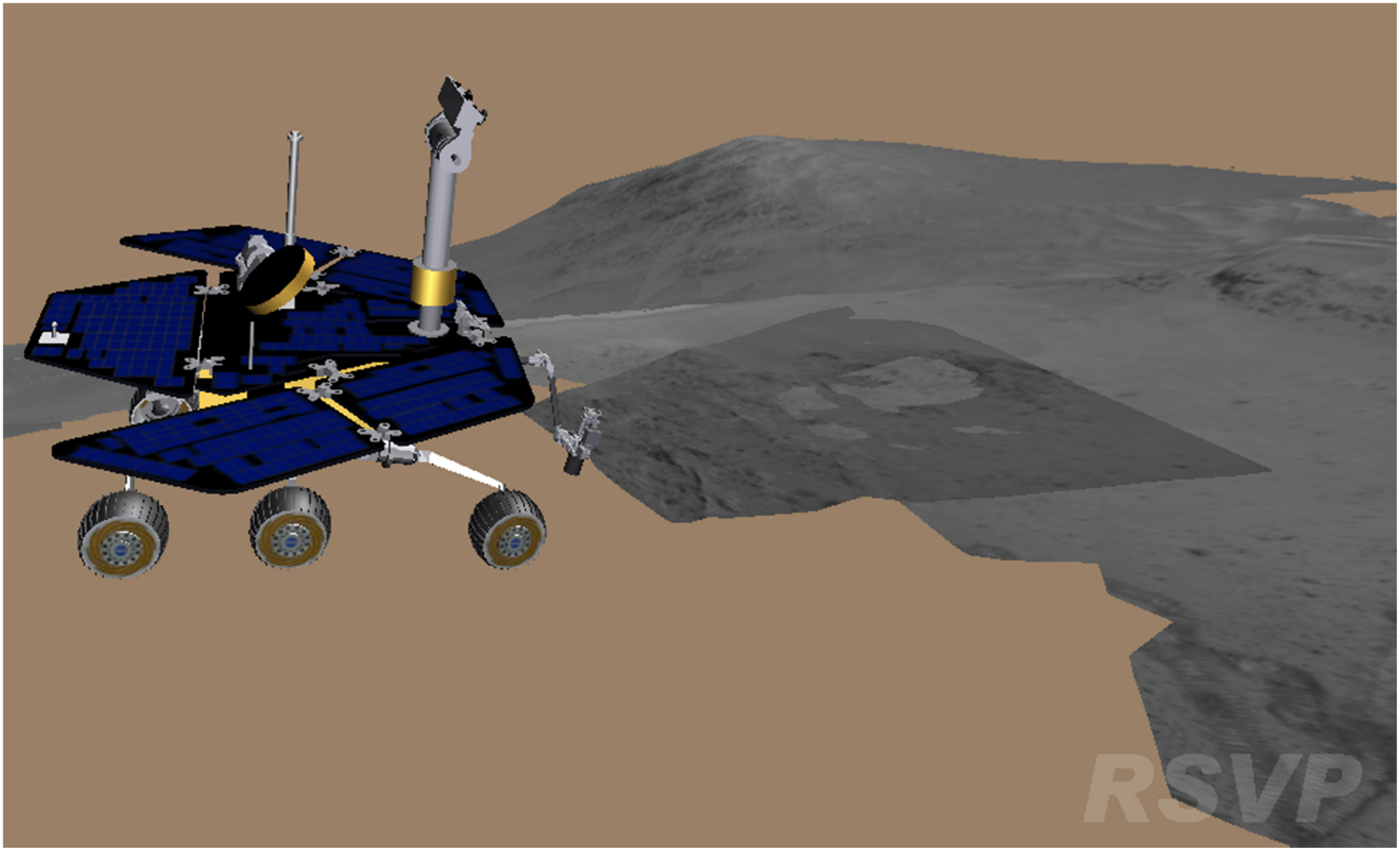
Algorithm Overview - Range Error Maps

- **New product, still under development**
- **Per-pixel error estimate**
  - Both cross/down range, and axis-aligned
- **Given disparity error, project perturbed rays to determine error volume**
- **Calculating disparity error is currently being worked on**
  - Correlation coefficient
  - Compression level
  - Scene activity
  - … ?
- **Eventually include terms for camera model error**

Algorithm Overview – Meshes

- **Converts XYZ point cloud to an octree representation**
  - Facilitates merging of multiple XYZ images to unified mesh
- **Creates polygonal (triangle) representation of surface**
  - Extracts connectivity from XYZ image
  - Uses octree to achieve tiling and multiple resolutions
- **Texture Mapping**
  - Uses imagery as mesh "skin"
  - Camera model is used to transform 3D mesh vertex -> 2D image coords -> 2D UV texture coords
- **Height map (DEM) also produced for driving simulations**
  - Simple and fast lookup to settle the rover
- **Mesh is in Open Inventor (MSL) or SGI Performer (MER) format**
  - Tiled, multiple levels of detail, strips of triangles, binary format
  - Not easily usable by other tools
  - Converter to standard OBJ format is being implemented

Terrain Mesh



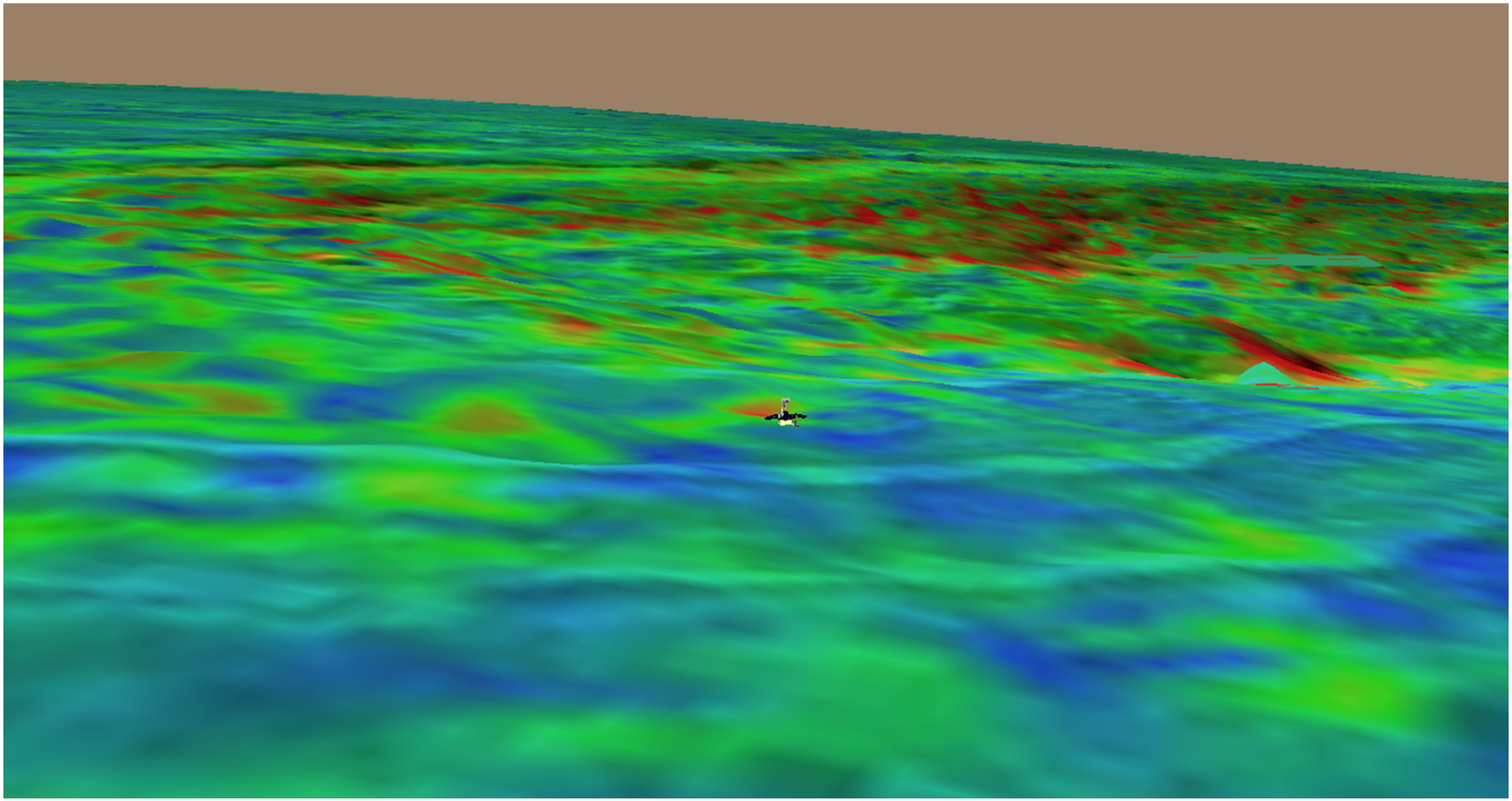
Automated Pipeline

- **Creation of these products (and others not covered here) is handled by an automated pipeline**
  - MER: Very large sh (Bourne shell) script
  - MSL: MATIS pipeline manager, written in Java around JBOSS JBPM.
- **Pipelines are automated**
  - Runs whenever data arrives, even if no operator
  - Exception: on MER, meshes must be manually started
    - Automated for MSL
- **Private pipelines allow special products and configurable results**

Orbital Imagery

- **Meshes from HiRISE DEMO and Ortho projection map created using same tools**
- **Flat mesh (when DEM not available)**
  - Texture mapping of Ortho projection into single polygon
  - Has proven tremendously valuable for planning long (~100m) drives of Opportunity across the mostly flat Meridiani plains
  - Localized to current Site frame, same as in-situ meshes
  - Used in RSVP (Rover Planner's visualization tool) just like standard meshes
- **DEM-based HiRISE meshes**
  - DEM is converted to point cloud
    - Need not be same scale as image
  - Generate synthetic camera model from high above for texture map
  - Baseline for MSL
  - Being deployed now for MER to aid navigation of Opportunity around Endeavor crater
  - Supports Slope and other overlays as texture maps

Orbital mesh w/slope overlay

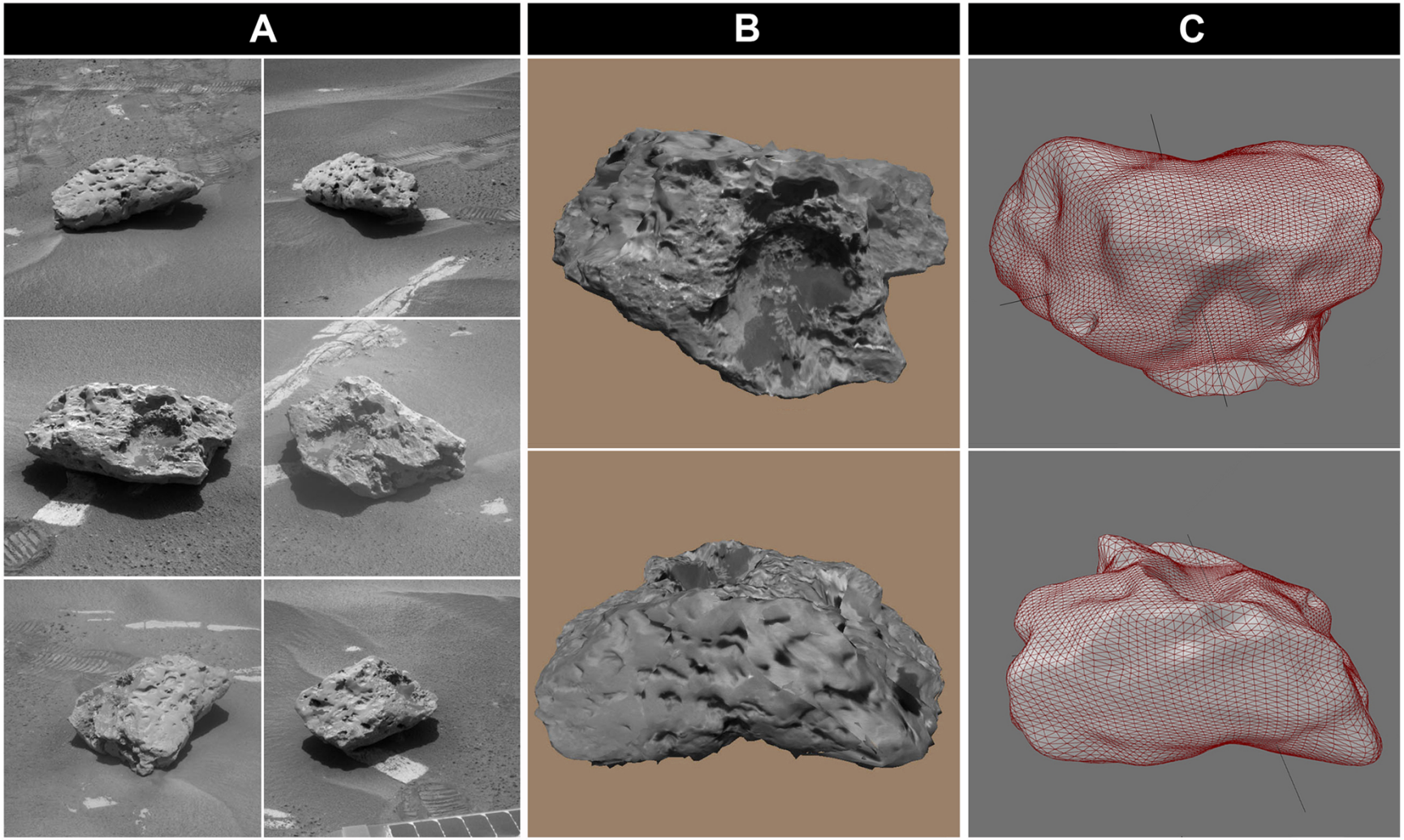


Opportunity sol 2965. 0-20 degrees mapped to blue->red

Block Island Meteorite

- **On Sols 1959-2009, Opportunity visited an interesting meteorite**
  - Drove all the way around, taking pictures from 6 vantage points
- **Images were combined into a single mesh**
  - Extensive coregistration process
- **Model was "shrink wrapped" to create solid volume**
  - Volume was then estimated for science use
    - Chappelow, J.E. and M.P. Golombek, "Events and conditions that produced the iron meteorite Block Island on Mars", J. Geophys. Res., 115, E00F07, doi:10.1029/2010JE003666, 2010
- **Multi-view analysis would have helped here**

Block Island results



Conclusion

- **The terrain generation suite has proven successful**
  - Integral part of daily ops cycles for MPF, MER, PHX, MSL
- **Work continues to improve it**
  - Error metrics
  - Orbital meshes
  - Algorithm improvements
  - XYZ-based registration and alignment of overlap areas
  - More mesh formats
- **Questions?**
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